# Influence of Alley Crop Environment on Orchardgrass and Tall Fescue Herbage

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## ABSTRACT

**The design of agroforestry systems requires a thorough understanding of biological interactions that might complement or constrain production. The objective of this study was to examine effects of alley crop environment on persistence, herbage yield, nutritive value, and gas exchange ($CO_2$ exchange rate, transpiration, and stomatal conductance) of two shade-tolerant herbage grasses. The experiment was conducted for 3 yr in orchardgrass (*Dactylis glomerata* L.), tall fescue (*Festuca arundinacea* Schreb.), and a 1:1 binary mixture (tall fescue and orchardgrass) in 4.9-m-wide alleys of 10-yr-old loblolly pine (*Pinus taeda* L.) and shortleaf pine (*P. echinata* Mill.), and the unshaded control at Booneville, AR. Loblolly pine was 1.5 m taller and had twice the canopy cover as shortleaf pine (52 and 25% canopy cover, respectively). Averaged across harvests, orchardgrass persisted better in loblolly pine alleys (72% stand) than in the control (44% stand) while tall fescue persisted better in the control (30% stand) than in loblolly pine (13% stand). Persistence in shortleaf pine alleys was intermediate for both herbage treatments. Yields of orchardgrass and the binary mixture did not differ in pine alleys (1300 kg ha$^{-1}$) and were usually greater than tall fescue yields ($\leq$700 kg ha$^{-1}$). Crude protein was higher in loblolly pine alleys (172 g kg$^{-1}$) than in the control (141 g kg$^{-1}$). Gas exchange parameters were similar for tall fescue and orchardgrass across a range of volumetric soil moisture (15–30%), indicating little difference in drought response. Producers should consider using orchardgrass monocultures or binary mixtures with tall fescue for pine alleys in the midsouth USA.**


The use of land resources can be increased when herbage, livestock, and wood fiber production are integrated in maturing loblolly pine plantations (Clason, 1999). Alley crop productivity is influenced by many factors, including the interaction of crop and tree species in space and time. Potential herbage species for alley crop systems have been discussed (Clason and Sharrow, 2000; Garrett and McGraw, 2000), but further research is needed to assess alley crop productivity and sustainability in specific systems.

Tall fescue and orchardgrass have substantial shade tolerance and silvopastoral value (Blake et al., 1966; Clason and Sharrow, 2000). Tall fescue has broad adaptability, persistence, and nutritive value (Burns and Chamblee, 1979) and is the predominant cool-season herbage grass in the central highlands of Arkansas. Orchardgrass has a more narrow range of adaptation than tall fescue and is a minor pasture component in much of the USA. Orchardgrass is at its extreme southwestern range in the central highlands of Arkansas (Jung and Baker, 1973) and is at a competitive disadvantage in unshaded sites in southern USA when exposed to high summer temperatures (Van Santen and Sleper, 1996).

Neither orchardgrass nor tall fescue had significant yield reduction in pots exposed to 50% shade, and orchardgrass yield was not significantly reduced in 80% shade compared with unshaded growth (Lin et al., 1999). When grown at 14% ambient photosynthetically active radiation, orchardgrass produced more tillers per plant than most other grasses tested (Devkota et al., 1997). When grazed, however, orchardgrass did not persist well in conifer-shaded pasture in West Virginia (Belesky et al., 2001).

Overstory trees can either complement or constrain understory herbage production and nutritive value. Trees can favorably alter the understory microclimate (Feldhake, 2001) and protect herbage by reducing evapotranspiration during drought (Frost and McDougald, 1989), minimizing deleterious interactions of heat stress and high light intensity on photosynthesis of $C_3$ species (Lin et al., 1999) and reducing radiation frost damage (Feldhake, 2002) compared with unshaded herbage. Conversely, trees can reduce herbage production through shade, competition for soil moisture and nutrients, and allelopathy (Clason and Sharrow, 2000; Garrett and McGraw, 2000). The objective of this study was to examine effects of alley crop environment on persistence, herbage yield, nutritive value, and gas exchange of two shade-tolerant herbage grasses.

## MATERIALS AND METHODS

### Site Description

The experimental area was located near Booneville, AR (35°05′ N, 93°59′ W; 152 m above sea level), on Linker fine sandy loam (fine-loamy, siliceous, thermic Typic Hapludults). Loblolly, longleaf (*Pinus palustris* Mill.), and shortleaf pines were planted in a north–south orientation in spring 1992 in four-row blocks 30 m long, spaced 1.2 m within rows and 4.9 m between rows (Pearson, 1994).

Tree survival was 72 and 77% for loblolly and shortleaf pine, respectively, in 1999. Branches were pruned in 1999 to a minimum stem diameter of 8.5 cm (a height of about 2.3 m) and 9.0 cm (a height of about 3 m) for shortleaf and loblolly pine, respectively. This left about 40 to 50% of the canopy unpruned. Pruning debris was removed from the site. Trees were not thinned, except that a few broken trees were removed following a December 2000 ice storm. Longleaf pine survival was only about 20%, so survivors were removed in 1999 to create the unshaded control treatment (Fig. 1).

Alleys were sprayed with glyphosate [*N*-(phosphonomethyl)glycine] at 1.06 kg a.i. ha$^{-1}$ three times in summer 1999 to kill the existing sod of tall fescue and bermudagrass [*Cynodon dactylon* (L.) Pers.]. Topsoil sampled to 15-cm depth had a pH range of 5.3 to 5.7 and 8.5 and 92 mg kg$^{-1}$ available P and

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**Abbreviations:** CER, $CO_2$ exchange rate; IVDMD, in vitro dry matter digestibility; PLS, pure live seed.

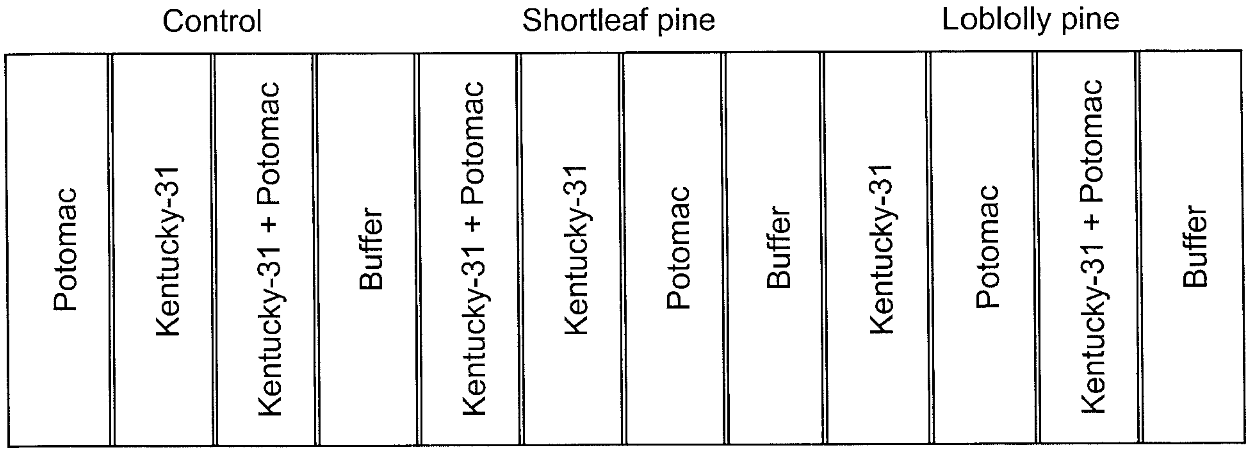


**Fig. 1. Diagram of one replicate in the experiment showing alley treatments (main plots) and herbage treatments (split plots). Alley treatments were randomized among replicates, and herbage treatments were randomized within alley treatments.**

K, respectively. Lime (3.4 t $ha^{-1}$) and fertilizer (56 kg $ha^{-1}$ each of N, P, and K) were applied in summer 1999. Soil was cultivated to 15-cm depth to prepare the seedbed and incorporate soil amendments.

Equal numbers of pure live seed (PLS) of 'Kentucky 31' endophyte [*Neotyphodium coenophialum* (Morgan-Jones and Gams) Glenn, Bacon, and Hanlin]-infected tall fescue, 'Potomac' orchardgrass, and 1:1 mixture of Kentucky-31 tall fescue and Potomac orchardgrass were broadcast-sown in September 1999. Seeding rate was 1230 PLS $m^{-2}$, equivalent to 24 and 30 kg $ha^{-1}$ seed of Potomac and Kentucky-31, respectively. Plots were at least 2.3 by 27 m and cultipacked before and after sowing. Plots were topdressed with N, P, and K fertilizer to supply 56 kg $ha^{-1}$ each of N, P, and K in the spring each year and after each harvest (Chapman, 1998).

## Environmental Monitoring

Environmental conditions were monitored with a Delta-T (Delta-T Devices Ltd., Cambridge, UK)[1] system consisting of a DL2e logger, six TM1 temperature thermistors, and three ML2 volumetric soil moisture sensors. One air temperature, soil temperature, and volumetric soil moisture sensor was placed in a loblolly pine alley, shortleaf pine alley, and control alley of replication two. Temperature sensors were placed 1 m above soil surface (air) or 15-cm depth (soil). Data were collected continuously at 1-h intervals during the March through October growing season in 2000 and 2001, except soil temperature was not collected in March 2001. Temperature and rainfall data also were collected in March–April 2002. Rainfall was measured in the control with a standard rain gauge.

Tree height, using a clinometer, and diameter breast height (1.3 m above ground surface), using a diameter tape, were measured annually from 1999 to 2001. Tree canopy cover was measured once annually in 2001 and 2002 at 1.3 m above ground surface in alley middles at four randomly selected locations within each tree plot using a CI-110 digital plant canopy imager (CID, Vancouver, WA).

[1] Disclaimer: Product names and trademarks are mentioned to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA does not imply the approval of the product to the exclusion of others that may also be suitable.

## Herbage Sampling and Analysis

Botanical composition (percentage orchardgrass, tall fescue, other grasses, and forbs) was measured for each plot using two-dimensional point quadrats (Wilson, 1959) before each harvest. Samples for herbage nutritive value were collected by hand-clipping seeded species at 3-cm stubble height from each plot immediately before yield harvests, drying in a forced-draft oven at 65°C for 72 h, and grinding to pass a 1-mm screen. Nitrogen was determined by combustion (LECO FP428, LECO Corp., St. Joseph, MI). Crude protein was calculated as N percentage × 6.25. In vitro dry matter digestibility (IVDMD) was determined using the procedure of Goering and Van Soest (1970), modified for the ANKOM Daisy II fiber analyzer #F200 (ANKOM Technol. Corp., Fairport, NY). Herbage samples from three replicates were analyzed at Harvests 3 and 4 for $NO_3$–N (see below). Tissue was extracted with hot water (97°C, 1 h), and the extracted $NO_3$–N was measured by the Cd-reduction method (Mulvaney, 1996) using a flow injection analysis instrument (FIAstar 5010 Analyzer, Foss Tecator, Höganäs, Sweden).

Plots were harvested for dry matter yield with a flail mower in April and October 2000 (Harvests 1 and 2) and with a rotary mower in April, June, and October 2001 and April 2002 (Harvests 3 to 6, respectively). Harvests were timed to simulate spring, late-spring, or fall hay harvests. Herbage was clipped at 5-cm stubble height, except for Harvests 5 and 6 when herbage was clipped at 8 cm. Clipped herbage from each harvest was collected in a hopper, weighed, and dried in a forced-draft oven at 65°C for 72 h for dry matter determination. Yield of seeded herbage was calculated from plot yield, percentage dry matter, and botanical composition.

## Leaf Gas Exchange

Rates of net photosynthesis or $CO_2$ exchange (CER), stomatal conductance, and transpiration were measured to determine shade response across a range of soil moisture. Measurements were taken on clear, sunny days between 0900 and 1100 h CST between June and October 2000 (nine dates) and 2001 (13 dates). Three tall fescue and orchardgrass plants were measured at two levels of irradiance, shade vs. sunpatch (Smith et al., 1989), in loblolly pine alleys on each sampling date. Plants had been in the sunpatch for ≥15 min before sampling while shaded plants received only minimal, diffuse radiation. Gas exchange measurements were made in the middle 10- to 15-cm region of attached, most recent, fully collared leaves using a CI-301PS portable gas analyzer (CID, Vancouver, WA). The instrument was calibrated according to the manufacturer's instructions and configured as an open system, ambient air temperature and relative humidity, constant $CO_2$ concentration of 360 ppm using a CI-301AD control unit, and 0.7 L min$^{-1}$ air flow. Five gas measurements were taken at 1-min intervals for each leaf and averaged. Gas exchange was not measured during periods of drought stress when tall fescue leaves were visibly curled. Water use efficiency (WUE, a unitless parameter) was calculated as the ratio of CER/stomatal conductance (Dickmann et al., 1992).

### Experimental Design and Statistical Procedures

The experiment was analyzed as a split-split plot design replicated six times. Alley environment, herbage treatment, and harvest were main plot, split plot, and split-split plot, respectively. Data were subjected to analysis of variance using the restricted maximum likelihood estimation method in the MIXED procedure of SAS (Littell et al., 1996; SAS Inst., 1998). Degrees of freedom were calculated by Satterthwaite's approximation method (Littell et al., 1996). All effects were considered fixed in determining the expected mean squares and appropriate *F* tests in the analysis of variance, except replication and interactions of replication with fixed effects. Botanical composition data were $\sin^{-1} y^{1/2}$ transformed before analysis (Steel and Torrie, 1980), but because this did not alter interpretations of *F* tests, data remained untransformed. Data were analyzed by repeated measures with a first-order autoregressive covariance structure [AR(1)], using harvests as the repeated effect (Littell et al., 1996). Means were separated using Fisher's protected LSD test at $P \leq 0.05$ (Steel and Torrie, 1980).

Temperature and soil moisture data were averaged across environments because environments did not differ ($P \geq 0.05$), and least-squares means and standard errors were computed for each year and month within year using the MIXED procedure of SAS (SAS Inst., 1998). Long-term air temperature and rainfall data were calculated from records of the Booneville Human Development Center, located about 2.5 km from the study site, for 1957 through 2000 (personal communication, 2001).

Water use efficiency was log10-transformed to assure normal distribution and homogeneity of variance (Steel and Torrie, 1980). Year, date within year, plant within date and year, year × species, irradiance × date within year, irradiance × year, and year × species × irradiance were random effects, and species, irradiance, and species × irradiance were fixed effects in the MIXED analysis (Littell et al., 1996). Gas exchange data also were regressed against volumetric soil moisture using the REG procedure (SAS Inst., 1998) to examine these relationships (Ellsworth, 2000).

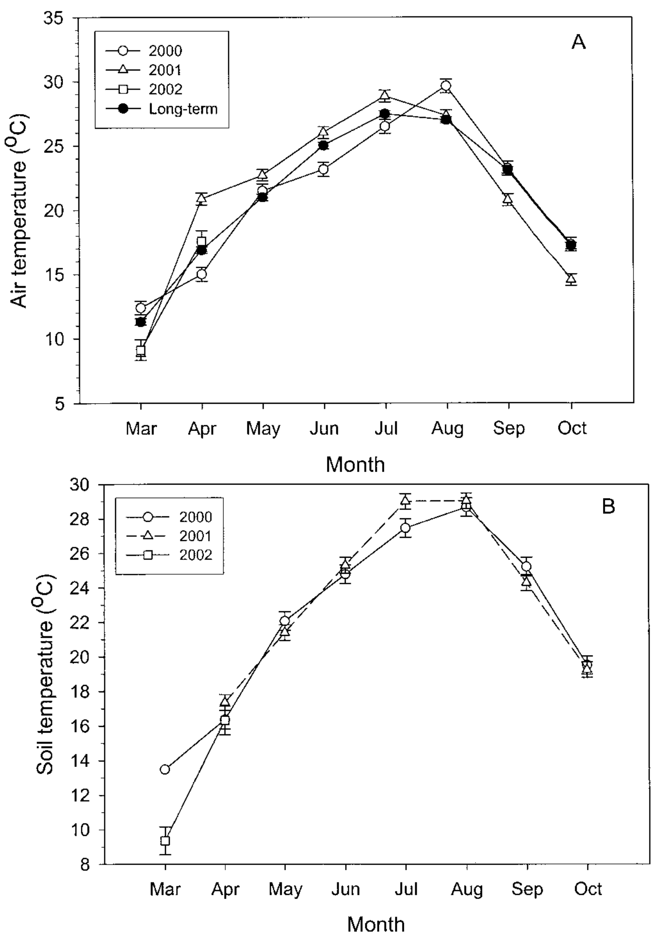


**Fig. 2. Mean monthly temperatures for the study period. (A) Air temperatures for March–October growth interval in 2000–2001, March–April 2002, and long-term mean (1957–2000). (B) Soil temperature for the March–October growth interval in 2000–2001 and for March–April 2002. Error bars indicate ± standard error of the mean.**

## RESULTS

### Alley Microenvironment

Mean air temperature for April to July tended to be above average in 2001 (Fig. 2A). Soil temperature differed little between 2000 and 2001 but was about 5°C cooler in March 2002 than in March 2000 (Fig. 2B). Rainfall for 2000 (531 mm) and 2001 (616 mm) was below average (702 mm) (Fig. 3). July and August were particularly dry in 2000 and 2001 compared with the long-term average, and herbage often appeared stressed

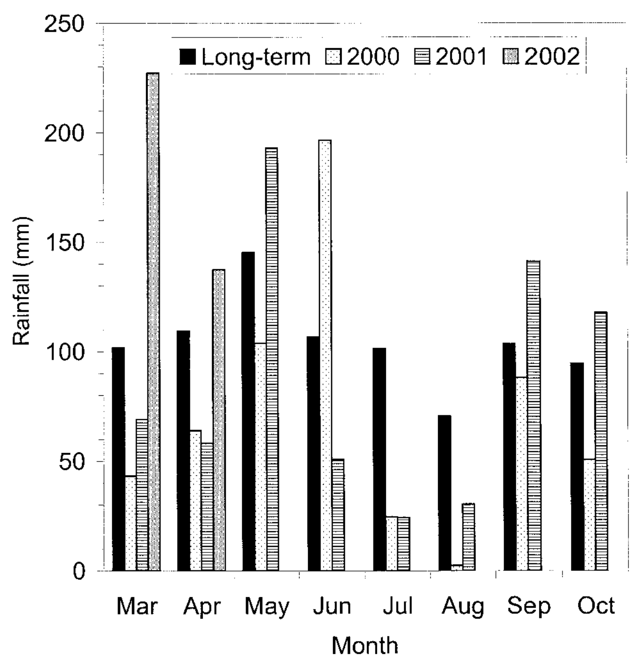


**Fig. 3. Monthly rainfall totals for the March–October growth interval in 2000–2001, March–April 2002, and long-term mean (1957–2000).**

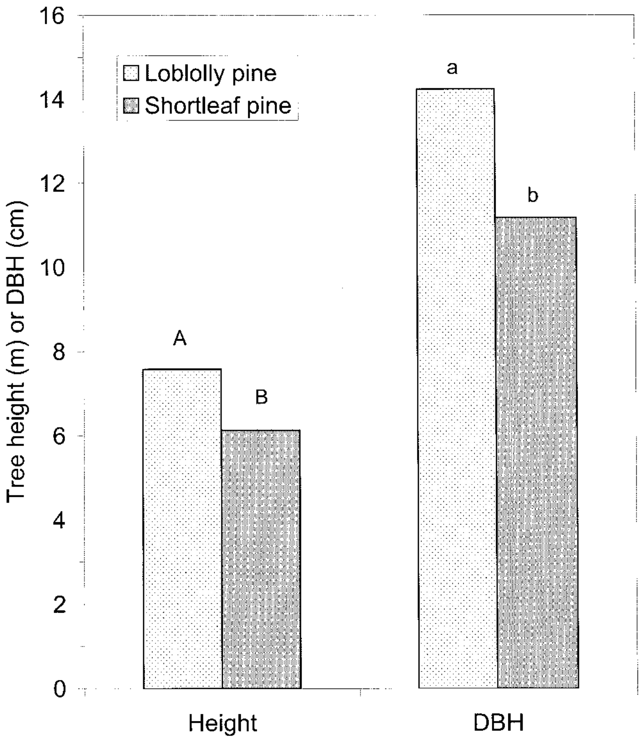


**Fig. 4. Mean height and diameter breast height (DBH) of loblolly and shortleaf pine. For each variable, letters indicate that species differed by *F* test ($P < 0.001$).**

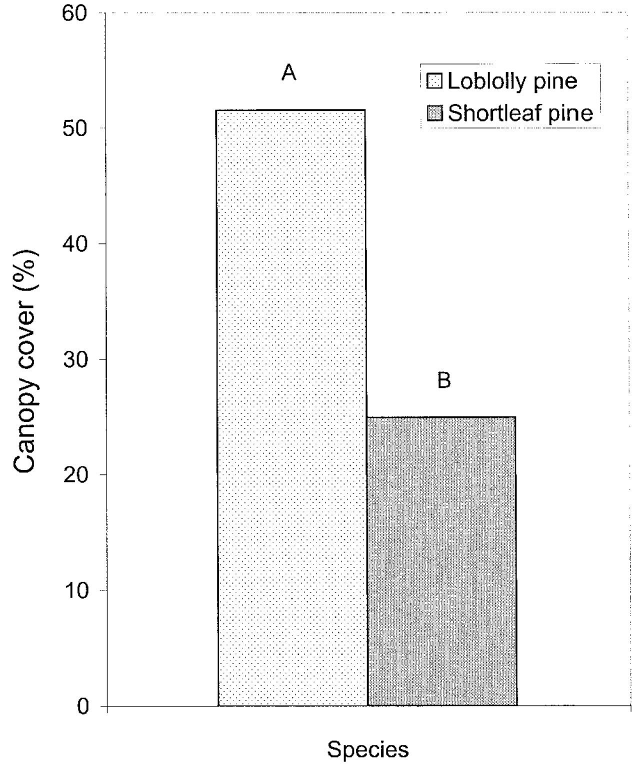


**Fig. 5. Mean canopy cover of loblolly and shortleaf pine measured annually at the center of alley between rows in 2001 and 2002. Letters indicate that species differed by *F* test ($P < 0.001$).**

during this period. Rainfall in March and April 2002 was above average.

Loblolly pine was taller and had greater diameter breast height ($P < 0.001$) than shortleaf pine during the 1999 to 2001 study period (Fig. 4). Loblolly pine also had nearly twice the canopy cover ($P \leq 0.001$) as shortleaf pine (Fig. 5).

## Botanical Composition

In April 2000, plots were dominated by the weedy, annual grasses cheatgrass (*Bromus tectorium* L.) and little barley (*Hordeum pusillum* Nutt.). In subsequent harvests, seeded species often comprised >65% of plot botanical composition. Other weedy grasses and grass-like species observed during the study included sedge (*Carex* spp.), crabgrass (*Digitaria* spp.), foxtail (*Setaria* spp.), and, in control, johnsongrass [*Sorghum halepense* (L.) Pers.]. Broadleaf weeds included henbit (*Lamium amplexicaule* L.), dock (*Rumex* spp.), horsenettle (*Solanum carolinense* L.), and white clover (*Trifolium repens* L.). Weedy grasses were more prevalent ($P = 0.01$) in tall fescue plots (22%) than in orchardgrass (16%) or the binary mixtures (14%).

**Table 1. Significance of *F* values for analysis of botanical composition from 2000 to 2002.**

| Source of variation | Percentage of sward as: Tall fescue | Orchardgrass | Other grasses | Forbs |
|---|---|---|---|---|
| Herbage | *** | *** | ** | NS† |
| Alley | *** | *** | NS | ** |
| Herbage × alley | NS | NS | NS | NS |
| Harvest × herbage | *** | * | NS | NS |
| Harvest × alley | *** | *** | ‡ | NS |
| Harvest × herbage × alley | NS | NS | NS | NS |

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NS, not significant at $P \leq 0.10$.
‡ Significant at the 0.10 level.

The change in botanical composition of seeded species across harvests was an indicator of persistence. The interaction of harvest with herbage species was significant ($P < 0.05$) for orchardgrass and tall fescue (Table 1). Persistence did not differ ($P \geq 0.10$) whether orchardgrass was sown as a monoculture or as a binary mixture with tall fescue (Fig. 6A). Surprisingly, volunteer orchardgrass was common (mean = 31% across harvests) in plots seeded with tall fescue. This was unexpected because orchardgrass was not a significant sward component at initiation of the study.

As expected, tall fescue was the dominant species in plots sown with tall fescue (Fig. 6B). However, when sown in a binary mixture with orchardgrass, tall fescue comprised only about 15% of the sward. Volunteer tall fescue occurred at a relatively low frequency (mean = 8%) in plots seeded with orchardgrass even though the initial sward was essentially a mixture of tall fescue and bermudagrass. Weedy grasses and forbs had no significant ($P \geq 0.10$) harvest × seeded species or harvest × alley interactions (Table 1).

Harvest × alley interactions were significant ($P \leq 0.001$) for tall fescue and orchardgrass composition (Table 1). Orchardgrass persisted better ($P \leq 0.05$) in loblolly pine alleys than in the control (Fig. 7A). Con-

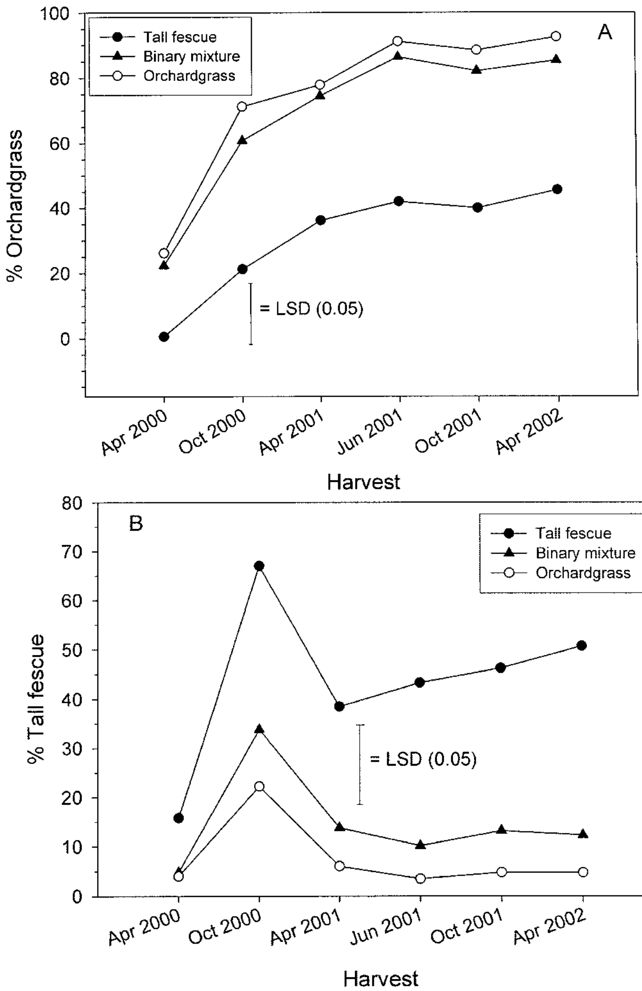


Fig. 6. Effect of harvest × herbage interactions on botanical composition measured six times in 2000–2002. Percentage of (A) orchardgrass and (B) tall fescue. Vertical bar indicates LSD ($P \leq 0.05$).

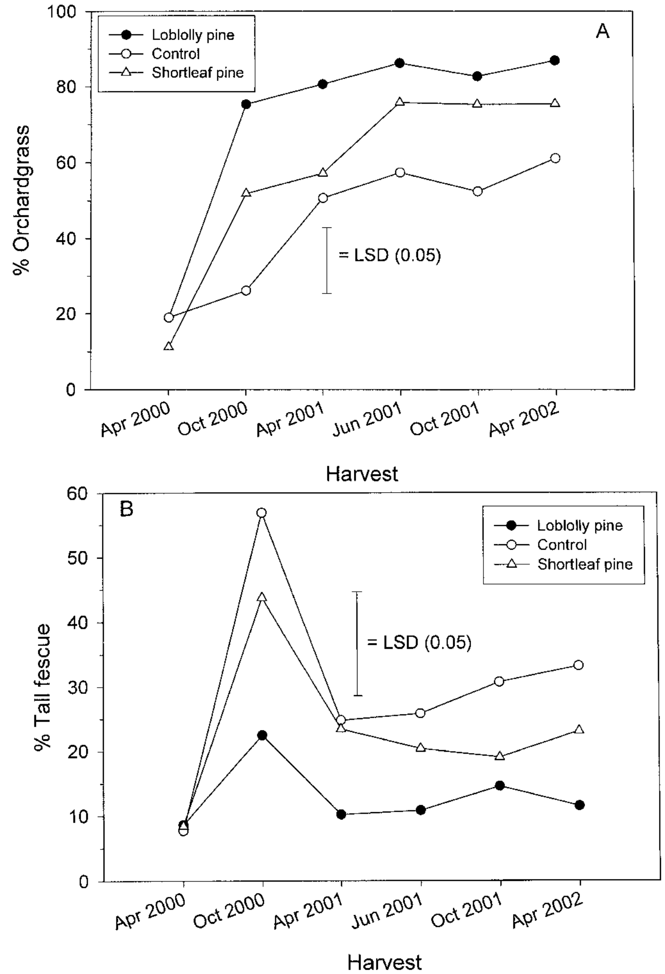


Fig. 7. Effect of harvest × alley interactions on botanical composition measured six times in 2000–2002. Percentage of (A) orchardgrass and (B) tall fescue. Vertical bar indicates LSD ($P \leq 0.05$).

versely, tall fescue tended to persist better in the control than in loblolly pine alleys (Fig. 7B). For both herbage species, persistence in shortleaf pine alleys tended to be intermediate to that in control and loblolly pine alleys. Averaged across harvests, orchardgrass persistence was better ($P \leq 0.05$) in loblolly pine alleys (72% stand) than in the control (44% stand) while tall fescue persistence was better ($P \leq 0.05$) in the control (30% stand) than in loblolly pine (13% stand).

## Herbage Yield

Harvest × herbage interactions were detected ($P \leq 0.001$) for both yield estimates (Table 2). For yield of all botanical components, the interaction seemed to be caused by change in ranking across harvests rather than difference in yield between herbage treatments (Fig. 8A). For yield of seeded species, orchardgrass and the binary mixture were comparable at most harvest dates (Fig. 8B), but tall fescue was lower yielding ($P \leq 0.05$) in 2001.

Harvest × alley interactions were detected ($P \leq 0.001$) for dry matter yield of all botanical components and seeded species (Table 2). Except for the April 2000 harvest, when weedy grasses dominated plots, both measures of dry matter yield responded similarly to harvest date (Fig. 9A and 9B). Yields tended to be higher in the control than in pine alleys. Across harvests, yield of all botanical components in pine alleys was about 70% ($P \leq 0.001$) of the control (1600 and 2300 kg ha$^{-1}$, respectively).

Dry matter yield of seeded species also had a significant ($P \leq 0.001$) alley × herbage interaction (Fig. 10). In the control, the binary mixture yielded more ($P \leq 0.05$) than either monoculture (1700 vs. 1300 kg ha$^{-1}$), and yields of orchardgrass and tall fescue did not differ ($P \geq 0.10$). The binary mixture yielded about 1300 kg ha$^{-1}$ in pine alleys, which was 25% less ($P \leq 0.05$) than in the control (1700 kg ha$^{-1}$). However, tall fescue yield in loblolly and shortleaf pine alleys (500 and 700 kg ha$^{-1}$, respectively) was less ($P < 0.05$) than yield of orchardgrass and the binary mixture (1100–1300 kg ha$^{-1}$).

## Herbage Nutritive Value

Crude protein had significant ($P \leq 0.001$) harvest × herbage and harvest × alley interactions (Table 2). For the harvest × herbage interaction, herbage treatments

**Table 2. Significance of *F* values for analysis of herbage yield, crude protein, $NO_3$–N, and in vitro dry matter digestibility (IVDMD) from 2000 to 2002.**

| | Dry matter yield | | | | |
|---|---|---|---|---|---|
| Source of variation | All botanical components | Seeded species | Crude protein | $NO_3$–N | IVDMD |
| Herbage | † | *** | *** | NS‡ | *** |
| Alley | *** | ** | *** | *** | † |
| Herbage × alley | NS | *** | NS | † | NS |
| Harvest × herbage | *** | *** | *** | NS | *** |
| Harvest × alley | *** | ** | *** | *** | NS |
| Harvest × herbage × alley | NS | NS | NS | † | NS |

** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† Significant at the 0.10 level.
‡ NS, not significant at $P < 0.10$.

changed in ranking among harvests (Fig. 11A). There were few differences among herbage treatments at any given harvest date, except that orchardgrass had higher concentration ($P < 0.05$) of crude protein than that of tall fescue in October 2001 and April 2002. Averaged across harvests, herbage treatments differed in crude protein according to the order orchardgrass (165 g kg$^{-1}$) > binary mixture (156 g kg$^{-1}$) > tall fescue (151 g kg$^{-1}$). The harvest × alley interaction may be explained by a proportional change in alley responses at the June 2001 harvest (Fig. 11B). Otherwise, crude protein increased with increasing canopy cover according to the order control (141 g kg$^{-1}$) < shortleaf pine (159 g kg$^{-1}$) < loblolly pine (172 g kg$^{-1}$).

Mean herbage $NO_3$–N was 23 μg g$^{-1}$ (range 9–47 μg g$^{-1}$) in April 2001 and 477 μg g$^{-1}$ (range 15–2001 μg g$^{-1}$) in June 2001, and there was a significant ($P < 0.001$) harvest × alley interaction (Table 2). Herbage $NO_3$–N increased in pine alleys between these harvest dates ($P < 0.05$), but control herbage did not (Fig. 12).

There was a significant ($P \leq 0.001$) harvest × herbage interaction for IVDMD concentration (Fig. 13). Or-

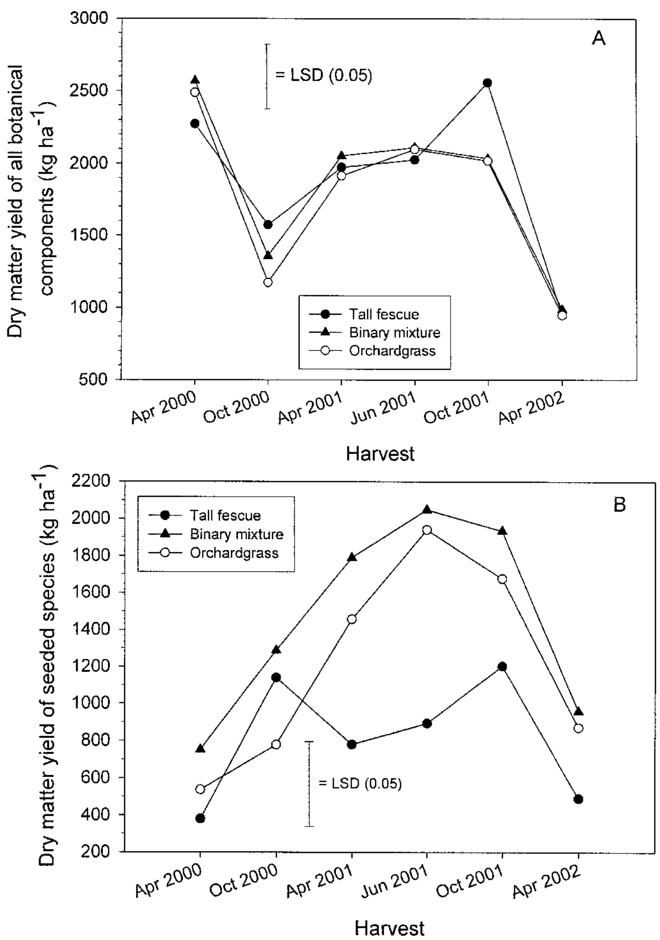


**Fig. 8. Effect of harvest × herbage interactions on dry matter yield measured six times in 2000–2002. Yield of (A) all botanical components and (B) seeded species. Vertical bar indicates LSD ($P \leq 0.05$).**

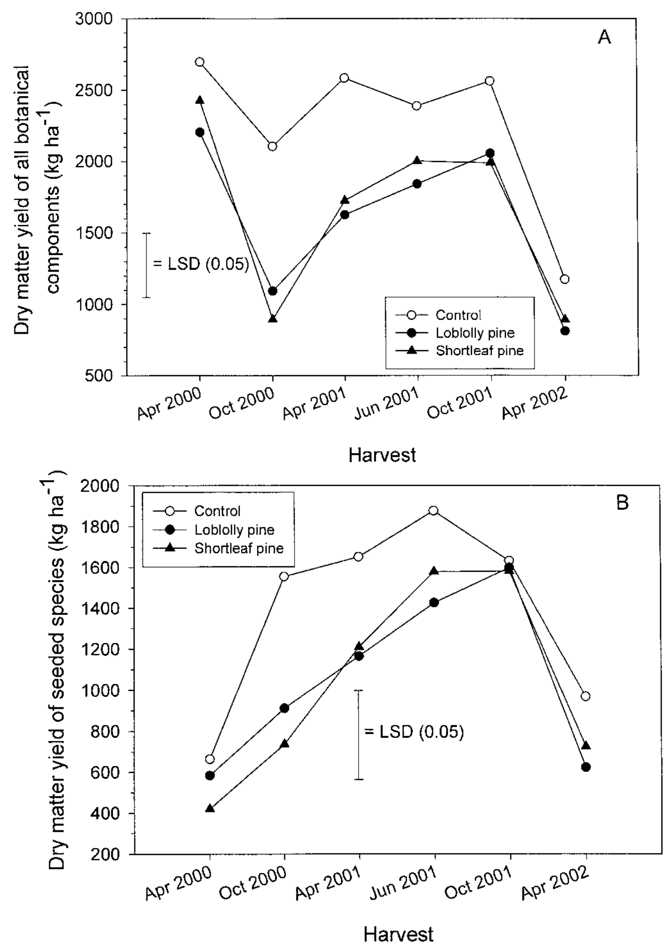


**Fig. 9. Effect of harvest × alley interactions on dry matter yield measured six times in 2000–2002. Yield of (A) all botanical components and (B) seeded species. Vertical bar indicates LSD ($P \leq 0.05$).**

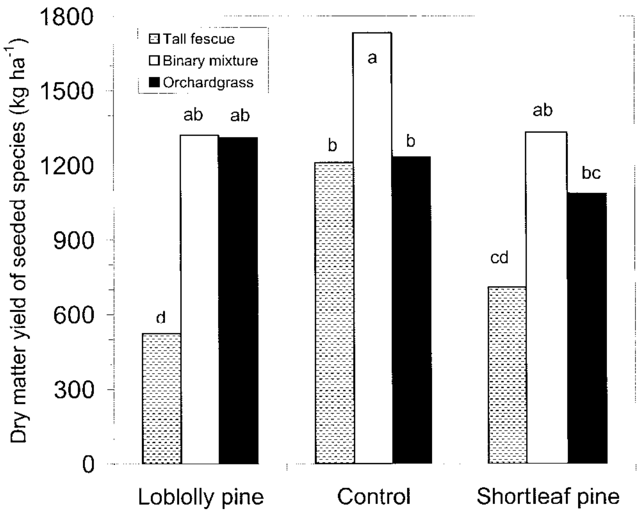


**Fig. 10. Effect of herbage × alley interactions on dry matter yield of seeded species. Letters indicate treatments differed by LSD (0.05) of 433 kg ha$^{-1}$.**

chardgrass and the binary mixture tended to have higher herbage IVDMD than that of tall fescue at each harvest.

## Herbage Physiology

Mean midday irradiances differed ($P < 0.001$) between shade and sunpatch treatments in loblolly pine alleys, 130 and 1470 μmol m$^{-2}$ s$^{-1}$, respectively. Compared with sunlit herbage, shaded herbage had lower ($P \leq 0.01$) transpiration (3.7 vs. 5.3 μmol m$^{-2}$ s$^{-1}$) and higher stomatal conductance (130 vs. 84 mmol m$^{-2}$ s$^{-1}$). However, shaded herbage also had lower ($P < 0.001$) CER (4.1 vs. 10.7 μmol m$^{-2}$ s$^{-1}$) and water use efficiency (1.6 vs. 2.2, respectively) than the sunpatch.

Gas exchange measurements provided little insight on the physiological basis for yield differences between the herbage species. Orchardgrass and tall fescue did not differ ($P > 0.20$) in CER (7.0 and 7.8 μmol m$^{-2}$ s$^{-1}$, respectively), but tall fescue had higher rates ($P \leq 0.05$) of transpiration (4.7 vs. 4.3 μmol m$^{-2}$ s$^{-1}$) and stomatal conductance (118 vs. 95 mmol m$^{-2}$ s$^{-1}$) compared with orchardgrass. Species × irradiance interactions were not significant for gas exchange parameters ($P \geq 0.13$). There was no significant change in physiological response across the range of volumetric soil moisture (15–30%), suggesting that tall fescue and orchardgrass differed little in drought response in pine alleys.

## DISCUSSION

The adoption of agroforestry practices in the USA is limited in part by inadequate knowledge of crop performance in tree alleys. The alley environment can be amenable to herbage production when designed and managed to accommodate light and soil moisture constraints. Nevertheless, herbage production usually is lower in agroforestry systems than in less competitive environments (Gillespie et al., 2000). In this study, herbage yield in pine alleys was about 70% of the control. Knowles et al. (1999) predicted zero pasture production when *Pinus radiata* D. Don reached about 70% canopy cover. The

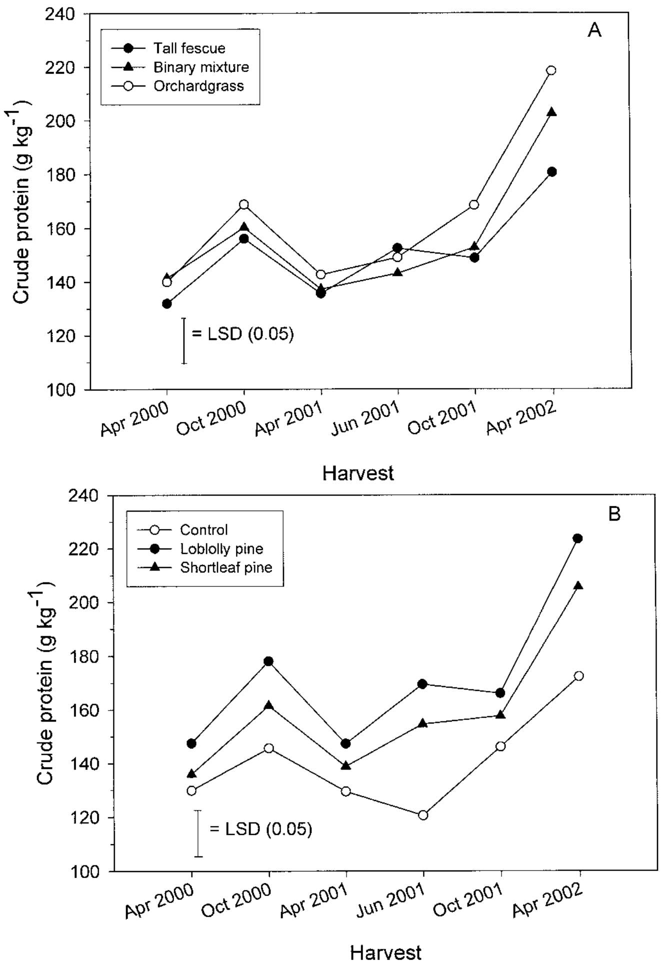


**Fig. 11. Mean herbage crude protein concentration harvested six times during 2000–2002. (A) Harvest × herbage and (B) harvest × alley interactions. Vertical bar indicates LSD ($P \leq 0.05$).**

data agree with those of Devkota et al. (2001), who concluded that canopy cover should be kept in the 40 to 50% range in deciduous tree silvopastoral systems to maintain pasture production at about two-thirds of the control.

Unlike tall fescue, orchardgrass persisted better under

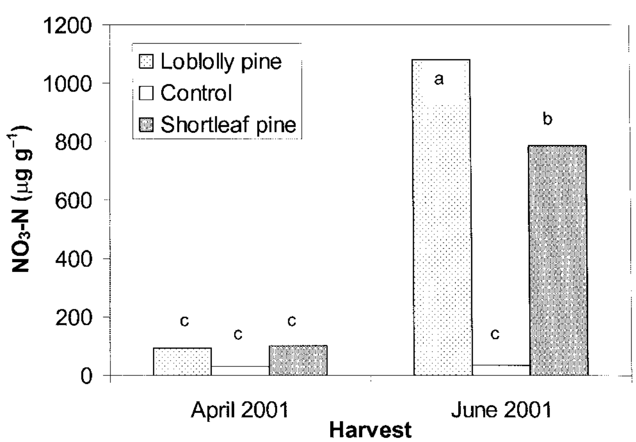


**Fig. 12. Effect of harvest × alley interactions on herbage $NO_3$–N measured twice in 2001. Letters indicate treatments differed by LSD (0.05) of 289 μg g$^{-1}$.**

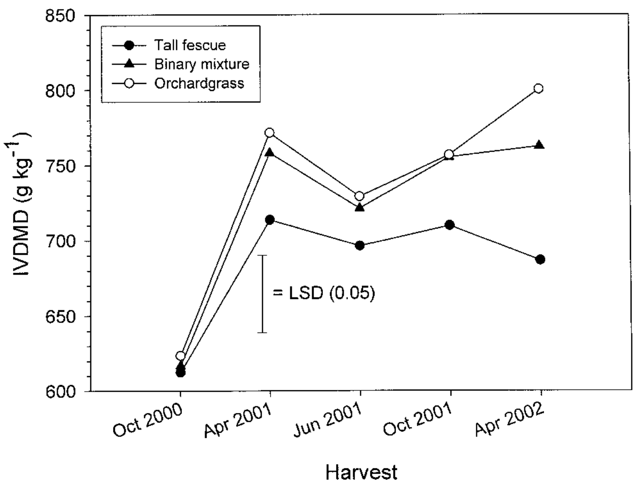


**Fig. 13. Effect of harvest × herbage interactions on herbage in vitro dry matter digestibility (IVDMD) measured five times in 2000–2002. Vertical bar indicates LSD ($P \leq 0.05$).**

the denser canopy of loblolly pine alleys and had higher dry matter yields. Burner and Brauer (2003) postulated that tall fescue was not sustainable in low-input swards in loblolly pine alleys subjected to only two (spring and fall) mechanical harvests per year. Thus, concerns remain about the sustainability of tall fescue monocultures in agroforestry systems. The introduction of livestock into this system could affect species persistence due to preferential grazing of orchardgrass. For example, orchardgrass did not persist well in conifer-shaded swards grazed by sheep (*Ovis aries* L.) in West Virginia (Belesky et al., 2001). Further, gaps in the sward due to reduced tillering (Devkota et al., 2001) could provide entry points for weeds. The relative persistence of orchardgrass and tall fescue in pine silvopastures needs further study.

Harvest × herbage treatment interactions indicated that nutritive value (crude protein and IVDMD) generally was higher for orchardgrass than tall fescue, with the binary mixture being intermediate. Herbage crude protein also tended to increase with shading. Crude protein is reportedly higher in shade-grown, cool-season grasses compared with unshaded treatments (Allard et al., 1991a; Burner and Brauer, 2003; Neel et al., 2001) although exceptions also have been noted (Peri et al., 2001; Watson et al., 1984). The relationship generally holds for warm-season grasses as well (Cruz et al., 1999; Smith and Whiteman, 1983). Shade, drought, and N fertilization can foster $NO_3$ accumulation by plants (Cash et al., 2002). Neel et al. (2001) caution that herbage $NO_3$ concentrations could reach toxic levels as tree shading increases. Our findings for two spring harvests indicate that $NO_3$ concentrations may indeed be problematic. Concentrations in pine alleys reached 790 to 1100 $\mu g\ g^{-1}$ $NO_3$–N, generally safe for nongestating livestock but approaching unsafe levels for gestating livestock (Cash et al., 2002).

Effects of shading on herbage IVDMD have been less well established than effects on crude protein. Herbage IVDMD of botanically complex, low-input herbage decreased with increasing alley width (Burner and Brauer, 2003). Allard et al. (1991a) found that IVDMD of tall fescue was unaffected by growth in the shade, and these data support their finding. Struik (1983) found that shaded maize (*Zea mays* L.) had lower digestibility than the control and suggested that shading affected cell wall content.

Light is the major environmental constraint to growth and reproduction of understory plants (Chazdon and Pearcy, 1991). Allard et al. (1991b) concluded that anatomical and physiological adaptations limit photosynthetic capacity and the ability to respond to increased irradiance and $CO_2$ of tall fescue grown continuously in the shade. Continuous, uniform shade rarely occurs in agroforestry systems because herbage receives direct and indirect illumination of varying duration and intensity during the day. Sunflecks or sunpatches account for 20 to 80% of the daily $CO_2$ exchange by understory plants (Pearcy, 1990). Grasses grown continuously at the suboptimal irradiance of pine alleys might be inherently less responsive to available sunlight, and lower yielding, than plants receiving full sunlight (Allard et al., 1991b). It seemed reasonable that water use efficiency was lower in shade vs. sun because of higher stomatal conductance in the shade. The physiological protection (lower transpiration) afforded by pine shade was more than negated by reduced CER. There was a higher rate of transpiration in tall fescue than orchardgrass, which could conceivably increase its susceptibility to drought stress and cause lower yield. However, herbage responses were comparable for CER, transpiration, and stomatal conductance across a range of soil moisture, suggesting little difference in drought tolerance.

Producers have considerable flexibility in designing agroforestry systems in terms of tree and alley crop species, alley width, tree row spacing, and management. Orchardgrass in monoculture or in binary mixture with tall fescue was more productive than tall fescue monoculture in this study. The most likely application of this design would be for silvopasture.

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